BRAIN RESEARCH 1242 (2008) 87–94

available at www.sciencedirect.com

www.elsevier.com/locate/brainres

BRAIN RESEARCH

Research Report

Selective effects of auditory stimuli on tactile roughness perception

Yuika Suzuki[a,*], *Jiro Gyoba*[a], *Shuichi Sakamoto*[b]

[a]*Department of Psychology, Graduate School of Arts and Letters, Tohoku University, 27-1 Kawauchi, Aoba-ku, Sendai, 980-8576, Japan*
[b]*Research Institute of Electrical Communication, Tohoku University, 2-1-1 Katahira, Aoba-ku, Sendai, 980-8577, Japan*

ARTICLE INFO

Article history:
Accepted 24 June 2008
Available online 2 July 2008

Keywords:
Crossmodal
Touch
Audition
Texture perception

ABSTRACT

We report two psychophysical experiments designed to investigate the effects of non touch-produced sounds on the tactile perception of roughness and length. Previous studies have demonstrated that the tactile roughness perception of object surfaces is modified by sounds elicited by rubbing the surfaces. In this study, we examined the crossmodal effects of non touch-produced sounds such as white noise (Experiment 1) and pure tones (Experiment 2). Participants touched abrasive paper, synchronizing their touch with changes in the intensity of sounds or with the onset of beeps (control condition), and judged the tactile roughness or length of the stimuli, using the magnitude estimation method. Although the white noise (complex sound) significantly decreased the slope of the roughness estimation function, it did not affect that of the length estimation function. Pure tones had no effect on roughness or length perception. The results revealed that complex sounds selectively affected tactile roughness perception, even when they were seemingly irrelevant to the exploration of the surfaces. We suggest that the processing of complex sounds may be related to the processing of tactile roughness, whereas it is independent of tactile length processing.

1. Introduction

In our daily lives, our experiences of interaction with objects and events are mostly multisensory (Driver and Spence, 2000; Spence and Zampini, 2006). For example, when we knock on a door, we can perceive the contact between the door and our hand, see the movement of our hand, and hear the sound produced by our action. In addition, we can simultaneously perceive the texture, temperature, hardness, and material characteristics of the door by automatically integrating multimodal information. Usually, when we touch an object and move our hands or fingers over its textured surface, sounds are elicited. Katz (1925, 1989) pointed out that moving tactile organs such as hands or fingers over surfaces produces a sense of pressure, which is usually accompanied by a sense of vibration closely linked to auditory perception.

It has been previously reported that when we perceive surface texture, tactile cues completely dominate auditory cues (Heller, 1982; Lederman, 1979). However, recent studies have demonstrated the effects of touch-produced sounds on tactile texture perception. Jousmäki and Hari (1998) reported that the roughness/wetness perception of palmar skin was altered by the feedback of the sound produced by rubbing both hands together. In their study, hand-rubbing sounds were fed back to participants via headphones, through which the amplitudes of the high-frequency components (i.e., above

* *Corresponding author*. Fax: +81 22 795 3703.
E-mail address: ysuzuki@sal.tohoku.ac.jp (Y. Suzuki).
URL: http://www.sal.tohoku.ac.jp/psychology/ysuzuki/ (Y. Suzuki).

0006-8993/$ – see front matter
doi:10.1016/j.brainres.2008.06.104

2 kHz) or of the overall frequency of the sound were manipulated. The participants were instructed to rate the texture of their palmar skin on a “rough/moist-smooth/dry” composite scale. The results showed that both types of amplifications led to the perception of a more paper-like sensation; that is, the participants' perception of the smoothness/dryness of their palmar skin increased. Therefore, this sound effect was termed “parchment-skin illusion”. However, the implications of the results were unclear as the response scale used by Jousmäki and Hari (1998) combined “roughness” and “wetness”. Therefore, Guest et al. (2002) separated the response scale in terms of “wet–dry” and “rough–smooth” and repeated the experiments. Guest et al. (2002) reported that the amplification of the high-frequency components of the auditory feedback increased the participants' perceptions of feelings of roughness and dryness of their palmar skin. In addition, their perception of dryness was also increased by overall amplification.

In addition to people's perception of the texture of their hands, Guest et al. (2002) showed the effects of auditory feedback on the roughness perception of abrasive papers. They used abrasives that contained particles of two sizes. Participants in their study were required to ignore sounds and distinguish the presented sample as either rougher or smoother. When the participants touched the abrasives, touch-produced sounds were either attenuated or amplified in the 2–20-kHz range and fed back to the participants via headphones. Their results showed that high-frequency attenuation decreased the participants' feelings of roughness of the tactile stimulus, whereas amplification increased their perception of roughness.

Lederman et al. (2002) used plastic plates and a probe for roughness estimations in three conditions: haptic, auditory, and bimodal. In the results, the haptic condition produced the roughest estimations, while the auditory condition produced the smoothest ones. The perceived roughness in the bimodal condition lay between the estimated roughness in the two conditions but closer to that in the haptic condition.

Suzuki et al. (2006) investigated the effects of touch-produced sounds via headphones on tactile roughness estimations by using abrasive paper with a wider range of particulate diameters (i.e., 0.015 to 0.275 mm) compared to that used in Guest et al. (2002). In the experiment by Suzuki et al. (2006), participants were instructed to ignore the sounds and make magnitude estimations of tactile roughness. Compared to the results of Lederman et al. (2002), which showed differences between modalities in the magnitude of estimated roughness, Suzuki et al. showed that the slope of the roughness estimation function with sound feedback was smaller than that without the feedback.

In contrast to these studies, Lederman (1979) reported no effects of auditory information when sounds were produced by making participants touch grooved aluminum plates with their bare fingers. This different result pertaining to crossmodal effects suggests that sounds need to be sufficiently loud in order to affect the perception of texture roughness, regardless of whether or not participants are required to ignore the sounds.

Even recent behavioral studies have shown the interaction between touch and audition (e.g., Caclin et al., 2002; Hötting and Röder, 2004; Bresciani et al., 2005; Menning et al., 2005; Gillmeister and Eimer, 2007). Neuroimaging studies on humans or macaque monkeys have provided evidence of cortical involvement in the integration of touch and audition, particularly in early processing stages, which has traditionally been considered to be unisensory (Murray et al., 2005). For example, a subregion of the human auditory cortex along the superior temporal gyrus (Foxe et al., 2002; Murray et al., 2005), the caudal auditory belt of macaque monkeys, that is, the second stage of the auditory cortex (Kayser et al., 2005), and the posterior parietal cortex and parietal opercula between the secondary somatosensory cortex and the auditory cortex (Gobbelé et al., 2003) have been found to be involved in the integration of sound and touch. Recently, using MEG, Caetano and Jousmäki (2006) demonstrated that vibrotactile input alone activated the auditory cortex in normal hearing adults. Moreover, Foxe et al. (2002) conducted an fMRI experiment and demonstrated auditory–somatosensory convergence in the human auditory association cortex. The somatosensory stimulus used in the study by Foxe et al. (2002) was sandpaper, while the auditory stimulus employed was a broadband stimulus whose frequency contents comprised band-passed white noise. The auditory stimuli were made similar to touch-produced sounds on sandpaper.

Some recent studies investigating the interaction between haptic and auditory information have used the virtual texture generated by the force-feedback device (McGee et al., 2001; Weisenberger and Poling, 2004; Kitamura et al., 2006) or the texture display mouse (Kim et al., 2007) as haptic stimuli; further, the auditory stimuli used in these studies were not real touch-produced sounds. For example, McGee et al. (2001) used sounds played to indicate contact with ridges/bumps on a virtual haptic surface, where the number of contact sounds was either congruent or incongruent. Weisenberger and Poling (2004) used a combination of two band-limited noises: one of them varied with the changing spatial frequency of the contact between the virtual surface and the probe, while the other varied with the horizontal velocity of the probe. Kitamura et al. (2006) used amplitude-modulated tones on the basis of studies in which auditory roughness had been measured for different sounds such as amplitude-modulated and frequency-modulated tones (e.g., Terhardt, 1974). Kim et al. (2007) used recorded sounds of sandpaper being rubbed, the intensity of the specific frequency band of the sound having been modified.

However, most previous behavioral studies on audiotactile interaction in texture perception used touch-produced sound feedback as auditory stimuli (Jousmäki and Hari, 1998; Lederman et al., 2002; Guest et al., 2002). Even though Schiller (1932) reported tone-affected texture perception in early period, since his study, few studies have quantitatively investigated the effects of non touch-produced sounds on the roughness perception of real materials. Tactile texture perception is strongly related to sounds produced during everyday experiences involving multimodal texture information as input. Complex sounds such as white noise are acoustically similar to touch-produced sounds in the sense that both contain broadband frequency components. Therefore, it is highly likely that such types of non touch-produced sounds also have an effect on tactile texture perception.

If the integration of tactile texture information and auditory information is done in automatic mode, it is possible that hearing a complex sound like white noise modifies tactile texture perception even though it does not affect other information related to the processing of touch (perception of shape, size, or length). In the intra-modal domain of touch, recent PET studies have reported that the discriminations of tactile roughness and shape/length activate different cortical regions (Roland et al., 1998). Therefore, we predicted that complex sounds selectively modify tactile roughness perception since the auditory processing of complex sounds may be associated with the tactile processing of roughness; however, they do not affect tactile length perception, which can be assumed to be processed independent of the processing of complex sounds.

Based on the abovementioned assumptions, we investigated whether or not the crossmodal effects of non touch-produced sounds such as white noise (Experiment 1) and pure tones (Experiment 2) can be observed in tactile roughness or length perceptions.

2. Results

2.1. *Results of Experiment 1*

In Experiment 1, the effects of white noise on tactile roughness and length were examined in comparison with those of beeps (control stimulus). The absolute magnitude estimations of tactile roughness or length were conducted in separate blocks.

For the white noise and short beep conditions, the mean magnitude estimates of perceived tactile roughness and length for each participant were logarithmically transformed and plotted as a function of the logarithmic grid size of each stimulus. From the equations obtained by the least squares method, the slopes and coefficients of determination of the equations were calculated for each participant.

Fig. 1 shows a typical example of individual data with regard to the roughness and length estimations for each sound condition. Fig. 2 indicates the roughness estimation and length estimation functions based on the mean slope and intercept for the participants in Experiment 1. One participant was excluded from the analysis because the slopes exceeded the mean beyond the value of twice the standard deviation. The slope data were then analyzed by a two-way repeated-measures ANOVA with sound (white noise/beeps) and task (roughness/length) as factors. The results showed that the sound×task interaction was significant (F (1, 8)=12.06, $p<0.01$). The simple main effect of the sound in the slopes was significant only during the roughness estimation (F (1, 16)=5.55, $p<0.05$). The post hoc comparisons by Ryan's method (where $p<0.05$ prior to correction) revealed that the slopes of the roughness estimation function in the white noise condition were significantly smaller than those in the control condition. In contrast, no significant effects of the white noise were observed in the slopes of the length estimation function.

We also conducted a two-way ANOVA for the coefficient of determination of the equations. No significant main effects were observed in the coefficient of determination of the equations for the sound or in the interaction between the sound and task.

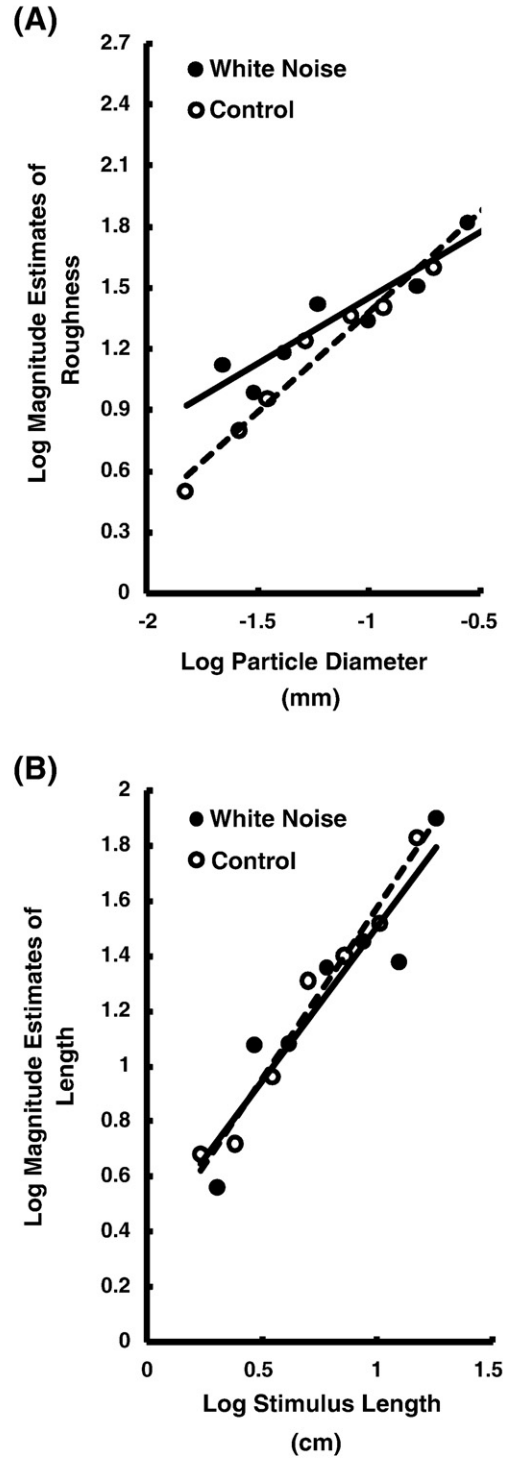

Fig. 1 – A typical example of the individual data for each sound condition. (A) the tactile roughness estimation function in the white noise condition ($y=0.64x+2.10$) and in the control condition ($y=0.98x+2.36$); (B) the tactile length estimation function in the white noise condition ($y=1.12x+0.39$) and in the control condition ($y=1.25x+0.33$).

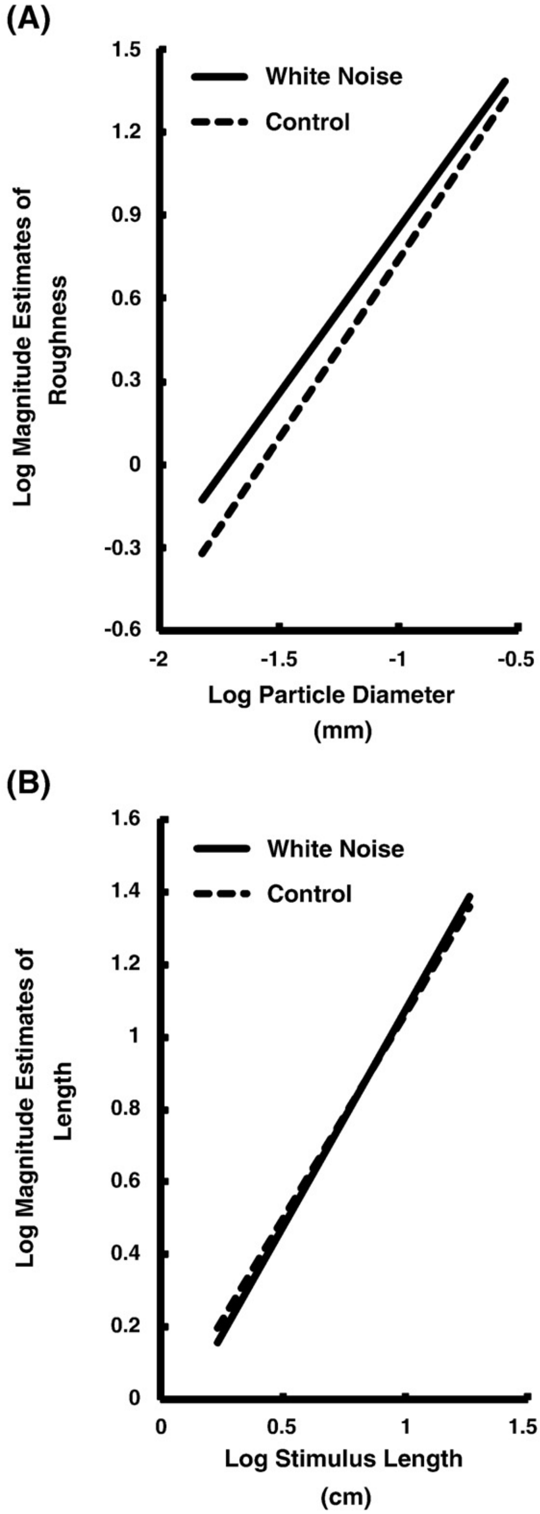

Fig. 2 – The averaged results for each sound condition. (A) the tactile roughness estimation function in the white noise condition (mean: $y=1.20x+1.20$) and in the control condition ($y=1.30x+1.13$); (B) the tactile length estimation function in the white noise condition ($y=0.94x+0.95$) and in the control condition ($y=0.92x+0.95$).

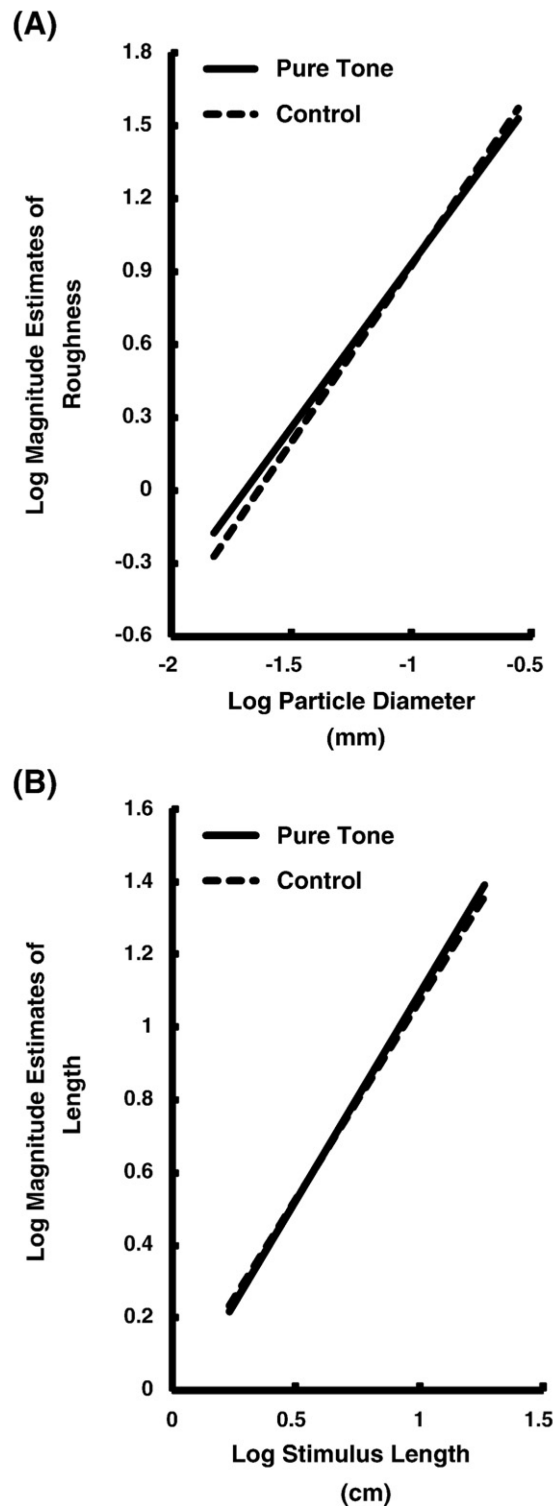

Fig. 3 – The averaged results for each sound condition. (A) the tactile roughness estimation function in the pure tone condition (mean: $y=1.35x+2.28$) and in the control condition ($y=1.47x+2.39$); (B) the tactile length estimation function in the pure tone condition ($y=1.14x-0.04$) and in the control condition ($y=1.10x-0.01$).

2.2. Results of Experiment 2

Experiment 2 aimed at investigating the effects of pure tones—another type of non touch-produced sound comprising a single frequency—on tactile roughness and length perceptions. The experimental procedure was the same as that in Experiment 1 except that 1000-Hz pure tones were used instead of white noise.

Similar to Experiment 1, for the pure tone and short beep conditions, the slopes and coefficients of determination of the roughness/length estimation functions were calculated for each participant.

Fig. 3 shows the roughness estimation and length estimation functions based on the mean slope and intercept for the participants in Experiment 2. The slope data were then analyzed by a two-way repeated-measures ANOVA with sound (pure tone/beep) and task (roughness/length) as factors. No significant main effects or interaction between sound and task were observed for either sound. In addition, there were no significant differences in the coefficient of determination of the equations.

3. Discussion

This study psychophysically investigated whether or not the tactile perception of roughness is selectively modified by non touch-produced auditory stimuli. In Experiment 1, we examined whether tactile roughness perception was selectively affected by white noise, which served as the non touch-produced sound. The results showed that when the participants touched tactile stimuli while synchronizing their finger movements with the intensity change of the white noise, the slopes of the tactile roughness estimation function became significantly smaller as indicated in Figs. 1A and 2A; however, the white noise did not affect the slope of the tactile length estimation function as shown in Figs. 1B and 2B. The results of Experiment 1 suggested that tactile roughness perception was modified selectively by complex sounds—such as white noise—that include a wide range of frequency components. However, it is possible that the crossmodal effect of white noise on tactile roughness perception, observed in Experiment 1, was caused by the mere existence of sound and not due to the complex sound. Therefore, Experiment 2 was conducted to examine whether another type of non touch-produced sound could modify tactile roughness perception, using 1000-Hz pure tones. The results showed that in comparison to white noise, pure tones affected neither tactile roughness perception nor length perception.

The crossmodal effects of white noise on tactile sensation are consistent with the results of Kitagawa et al. (2005), which showed that white noise distractors interfered more strongly than a pure tone, with speeded left/right discrimination responses to electrocutaneous targets. Considering audiotactile interaction in the spatial domain (Kitagawa et al., 2005), the difference between the crossmodal effects in the white noise and pure tone conditions is assumed to exist not only due to the acoustical similarity between the noise and sounds generated by sliding fingers on abrasive paper but also because this difference reflects ecological validity, since most sounds in the natural environment contain a broad spectral distribution rather than a single frequency component (Moore, 1989).

The experimental procedure in the present study (i.e., the participants were told to move their fingers in sync with the sounds) made the participants clearly aware that white noise (and also beeps) was not elicited by them moving their fingers on tactile stimuli. Nevertheless, when they moved their fingers in sync with the change in the intensity of white noise, their tactile roughness perception was modified. With regard to this point, Weisenberger and Poling (2004) conducted a roughness discrimination task involving multimodal virtual surfaces and indicated that the discrimination performance of virtual texture roughness for two and three modality conditions was not always better than that for single modality conditions. They suggested the possibility that when stimuli were presented using multisensory modalities, the observers were unable to selectively attend to or ignore a particular modality even when the modality was a poor channel for the task. In the study by Weisenberger and Poling (2004), stimuli from different modalities were congruent with regard to information on texture. In contrast, the auditory stimuli used in the present study were substantially non-informative. The crossmodal effects observed in this study indicated that when information from different modalities was received in sync with participants' own movement of sensory organs, it was difficult to ignore information from different modalities even if the items of information were irrelevant to each other.

In fact, it is important that the active synchronization of participants' finger movements with the sounds maintain crossmodal effects. Multimodal binding is typically broken by delays—of approximately 75–120 ms—between modalities (Bertelson and Aschersleben, 1998; Calvert et al., 1998; Driver and Spence, 2000). Jousmäki and Hari (1998) reported that adding a delay of more than 100 ms between the rubbing of the hands and the audio feedback from the hands diminished the parchment-skin illusion.

There is a possibility that synchronizing finger movements with sound changes affected the auditory effects on tactile roughness. In our preliminary study, when participants were not told to synchronize their finger movements with the sound changes, a significant effect of white noise was not observed. The difference between the results cannot be explained by attentional effect because in Experiment 2, pure tones had no effect on tactile roughness.

For the purpose of measuring the time difference between the onset of sound intensity changes and finger movements in each sound condition, we conducted a complementary experiment ($N=4$). We measured the temporal differences for three auditory conditions (white noise, pure tones, and beeps) and four tactile stimuli (coarsest, finest, longest, and shortest) in the analysis, using a digital video camera.

The results indicated that active movements were delayed by approximately 100 ms from the onset of the sound intensity changes in all conditions. On average, the observed delays were similar in all three sound conditions (noise: 109 ms, tone: 104 ms, beep: 120 ms for roughness stimuli; noise: 113 ms, tone: 88 ms, beep: 105 ms for length stimuli). Therefore, the finding that the effect of sounds on tactile roughness is observed only for white noise cannot be attributed to these delays.

These observed delays between active finger movements and sounds were not marginal, i.e., they were approximately 100 ms; however, they were shorter than simple RTs due to anticipatory responses. Bresciani et al. (2005) reported that the temporal window of audiotactile integration might be wider (at least more than 155 ms) than that for audiovisual integration. Therefore, the temporal gap between the sound onset and finger movements might be within the temporal window of audiotactile integration.

Future studies should carefully investigate the temporal restriction of synchrony between the touching of the stimuli and the onset of auditory information, as well as the differences between active and passive touch, for producing crossmodal interaction in roughness perception.

We also measured the intensity of the touch-produced sounds that were heard from outside the headphones (closed headphones were employed) by using a microphone (Brüel and Kjær; 4134), an artificial ear (Brüel and Kjær; 4153), and a measuring amplifier (Brüel and Kjær; 2610). The measured levels of the sounds produced by rubbing the abrasives were considerably weak. The difference in the overall sound pressure levels between the condition involving the rubbing of the coarsest abrasive sample and that without the rubbing was approximately 1.45 dB when the sound stimuli were not presented.

In addition, Lederman (1979) reported that auditory information did not affect the roughness estimations when weak sounds were produced by making the participants touch grooved aluminum plates with their bare fingers. She indicated that sounds need to be sufficiently loud so as to affect the perception of texture roughness (Lederman et al., 2002).

Therefore, in our experiments, even if the touch-produced sounds were audible to some extent from outside the headphones, it can be assumed that the rubbing sounds were not substantially effective with respect to roughness perception.

The present study revealed the presence of crossmodal effects despite the presence of spatially different tactile and auditory stimuli. The sounds were presented via headphones and the tactile stimuli were presented on the participants' hands. However, a number of studies have shown that multisensory interactions are subject to limitations of spatial misalignment and temporal asynchrony of stimuli (e.g., Harrington and Peck, 1998; Forster et al., 2002). In contrast, several studies investigating audiotactile interactions have presented auditory and tactile stimuli from different spatial locations as has this study and have shown the existence of crossmodal interactions (e.g., Adelstein et al., 2003; Gillmeister and Eimer, 2007; see Kitagawa and Spence, 2006 for review). In addition, psychophysical and electrophysiological studies have demonstrated that auditory–somatosensory interactions in humans occur via the same early sensory mechanism when stimuli are in or out of spatial register (Murray et al., 2005). Gillmeister and Eimer (2007) suggested the possibility that the peculiar spatial relationship between auditory and tactile stimuli reflects the inferior spatial resolution of these modalities and is related to the fact that auditory and tactile stimuli are represented more bilaterally than are visual stimuli.

The present study demonstrated that white noise modified the slope of the tactile roughness estimation functions but did not affect the length estimation functions. The results suggest that the auditory processing of complex sounds and the tactile processing of roughness are related to each other. However, the auditory processing of complex sounds appears to be unrelated to the processing of tactile length. Roland et al. (1998) reported that tactile roughness discrimination activated the lateral parietal opercular cortex more than tactile shape and length discrimination did, while shape and length discrimination activated the cortical field lining the anterior part of the intraparietal sulcus more than roughness discrimination did. In an fMRI study, Foxe et al. (2002) reported that the human auditory association cortex may be involved in integrating auditory and tactile signals for texture perception. At present, there are no neuroimaging studies that clearly demonstrate evidence of integration between the processing of tactile roughness and non touch-produced sounds. Therefore, it is necessary to conduct further investigation into the neural basis responsible for the results of the present study.

We demonstrated that white noise decreases the slope of the roughness estimation function. This result may indicate that white noise diminishes the difference in perceived tactile roughness. This does not imply that white noise renders the task of magnitude estimations more difficult because white noise does not have a significant effect on the coefficient of determination of the equations. Another possibility is that white noise has unequal effects across a wide range of surfaces and that it results in the tactile roughness sensation becoming stronger, particularly in the case of finer surfaces. If the results reflect inverse effectiveness, which means that the greatest enhancements occur for multisensory combinations of the weakest sensory stimuli (e.g., Meredith and Stein, 1986; Gillmeister and Eimer, 2007), the crossmodal effects of the sounds are greater for finer surfaces than for coarser surfaces. In order to investigate this possibility, we are planning to examine the relationships between stimulus range (e.g., the particle size of abrasive paper) and the effects of sounds on tactile roughness perception by using surfaces that are finer than those of the stimuli used in this study.

4. Experimental procedures

4.1. *Experiment 1*

4.1.1. *Participants*

Ten consenting subjects (6 men and 4 women aged 21–30 years) participated in Experiment 1. All the participants identified themselves as right-handed and reported no cutaneous or hearing problems. None of the participants had any prior experience in conducting absolute magnitude estimations.

4.1.2. *Stimuli and apparatus*

Auditory stimuli were produced and presented on a laptop, using Matlab 6.5.2 (Mathworks Inc.) and the Cogent 2000 toolbox (http://www.vislab.ucl.ac.uk/cogent/index.html). Each auditory stimulus was presented via headphones (Audio-Technica ATH-PRO700).

As tactile stimuli, silicon carbide abrasive paper of 14 different particle sizes (grid value: 60–1200, particle diameters: 0.015–0.275 mm) was used for the roughness estimation, while abrasive paper of 14 different lengths (1.7–18.0 cm; all the stimuli were 3 cm wide and of the same grade, i.e., 240) was used in the length estimation. As auditory stimuli, white noise whose intensity (63, 68, 73, and 77 dBSPL) changed at 1-sec intervals in pseudorandom order was used. The control stimulus comprised five beeps (1000 Hz, 64 dBSPL, 50 ms, SOA=1 s).

4.1.3. *Design and procedure*

The tactile roughness and length estimations were conducted in separate blocks for each participant. The participants wore headphones and touched the abrasive paper with the index and middle fingers of their dominant hand. Participants touched each tactile stimulus while synchronizing their finger movements with the change in intensity of the white noise or with the onset of short beeps.

Until the sound stimuli were presented, the participants placed their hand in preparation, on the given point and their index and middle fingers did not touch the tactile stimuli. They were instructed to begin their finger movements straight up to the other edge of the plate on which the abrasive paper was attached. At the same time as the intensity of the sounds changed (the white noise condition) or the short beeps were presented (the control condition), they had to change the direction of their finger movements at the edge of the plate toward the other edge. This made the rate of hand motion almost equal across the stimuli (approximately 22 cm/s), while Lederman (1974) reported that the exploration speed had a negligible effect on perceived roughness at least within the range of about 1–25 cm/s. The participants had sufficient time to explore all the tactile stimuli, and none of the participants reported that time was insufficient for the same.

The fingers of the participants completed the course of movement and returned twice. The moving direction was always horizontal, from side to side, for both the roughness and length estimations. The participants took their fingers off from the tactile stimulus at the same time as the sounds disappeared.

They were required to assign numbers, whose subjective magnitude matched their impressions, of how rough (in the roughness estimation task) or long (in the length estimation task) the surfaces were. Based on the absolute magnitude estimation procedure (e.g., Gescheider and Hughson, 1991), no standard or modulus was used, and the participants could use any subjective impression of roughness or length that they felt comfortable with. Prior to the experiments, the participants were trained in the method of absolute magnitude estimation, using the estimation of the weight of small boxes.

Fourteen tactile stimuli of different roughness and lengths were divided into two series of seven complementally selected samples and were presented in different auditory conditions (blocks) in a counterbalanced manner. The order of the task (roughness or length estimations) and the presentation of the auditory stimuli (white noise or beeps) were also counterbalanced among the participants. Each abrasive paper sample was presented three times in random sequence, and there was one practice trial.

In total, the participants judged both the roughness and length 56 times. The total duration of the experiment including the explanation was approximately 1 hour in both the experiments. In order to avoid the decline in the sensitiveness of their fingers, the participants were asked to take a short rest at any time if they felt their fingers were becoming less sensitive or if they experienced discomfort; further, they were given short breaks after every 28 trials.

From the individual data of the tactile roughness and length estimation functions, the slopes and coefficients of determination were calculated for each sound condition.

4.2. *Experiment 2*

4.2.1. *Participants*

Nine consenting subjects participated in Experiment 2 (4 men and 5 women aged 20–22 years). They did not participate in Experiment 1. All the participants claimed to be right-handed and reported no cutaneous or hearing problems. As in Experiment 1, none of the participants had ever before conducted absolute magnitude estimations.

4.2.2. *Stimuli and apparatus*

As auditory stimuli, instead of the white noise used in Experiment 1, 1000-Hz pure tones were used, which comprised four intensities (60, 65, 71, and 76 dBSPL) at 1-sec intervals in pseudorandom order. The sound intensities were preliminarily determined by the subjective matching of loudness with that of the white noise used in Experiment 1 ($N=3$). The apparatus was the same as that used in Experiment 1.

4.2.3. *Design and procedure*

The experimental procedure was the same as that in Experiment 1. Each experiment lasted for almost an hour.

Acknowledgments

This research was supported by a research fellowship awarded to the first author by the Japan Society for the Promotion of Science for Young Scientists (No. 20-5117) and by a JSPS Grant-in-Aid for Scientific Research (No. 18330151) awarded to the second author and by Grant-in-Aid of the Ministry of Education, Culture, Sports, Science and Technology for Specially Promoted Research (19001004) awarded to the second and the third authors.

REFERENCES

Adelstein, B.D., Begault, D.R., Anderson, M.R., Wenzel, E.M., 2003. Sensitivity to haptic-audio asynchrony. Proceedings of the 5th International Conference on Multimodal Interfaces, 73-76.

Bertelson, P., Aschersleben, G., 1998. Automatic visual bias of perceived auditory location. Psychon. Bull. Rev. 5, 482–489.

Bresciani, J.P., Ernst, M.O., Drewing, K., Bouyer, G., Maury, V., Kheddar, A., 2005. Feeling what you hear: auditory signals can modulate tactile tap perception. Exp. Brain Res. 162, 172–180.

Caetano, G., Jousmäki, V., 2006. Evidence of vibrotactile input to human auditory cortex. NeuroImage 29, 15–28.

Caclin, A., Soto-Faraco, S., Kingstone, A., Spence, C., 2002. Tactile 'capture' of audition. Percept. Psychophys. 64, 616–630.
Calvert, G.A., Brammer, M.J., Iversen, S.D., 1998. Crossmodal identification. Trends Cognit. Sci. 2, 247–253.
Driver, J., Spence, C., 2000. Multisensory perception: beyond modularity and convergence. Curr. Biol. 10, 731–735.
Forster, B., Cavina-Pratesi, C., Aglioti, S., Berlucchi, G., 2002. Redundant target effect and intersensory facilitation from visual–tactile interaction in simple reaction time. Exp. Brain Res. 143, 480–487.
Foxe, J.J., Wylie, G.R., Martinez, A., Schroeder, C.E., Javitt, D.C., Guilfoyle, D., Ritter, W., Murray, M.M., 2002. Auditory–somatosensory multisensory processing in auditory association cortex: an fMRI study. J. Neurophysiol. 88, 540–543.
Guest, S., Catmur, C., Lloyd, D., Spence, C., 2002. Audiotactile interactions in roughness perception. Exp. Brain Res. 146, 161–171.
Gescheider, G.A., Hughson, B.A., 1991. Stimulus context and absolute magnitude estimation: a study of individual differences. Percept. Psychophys. 50, 45–57.
Gillmeister, H., Eimer, M., 2007. Tactile enhancement of auditory detection and perceived loudness. Brain Res. 1160, 58–68.
Gobbelé, R., Schürmann, M., Forss, N., Juottonen, K., Buchner, H., Hari, R., 2003. Activation of the human posterior parietal and temporoparietal cortices during audiotactile interaction. NeuroImage 20, 503–511.
Harrington, L.K., Peck, C.K., 1998. Spatial disparity affects visual–auditory interactions in human sensorimotor processing. Exp. Brain Res. 122, 247–252.
Heller, M.A., 1982. Visual and tactual texture perception: intersensory cooperation. Percept. Psychophys 31, 339–344.
Hötting, K., Röder, B., 2004. Hearing cheats touch, but less in congenitally blind than in sighted individuals. Psychol. Sci. 15, 60–64.
Jousmäki, V., Hari, R., 1998. Parchment-skin illusion: sound-biased touch. Curr. Biol. 8, 190.
Katz, D., 1925/1989. The world of touch. Erlbaum, Hillsdale, NJ. (L. Krueger, Trans.).
Kayser, C., Petkov, C.I., Augath, M., Logothetis, N.K., 2005. Integration of touch and sound in auditory cortex. Neuron 48, 373–384.
Kim, S.C., Kyung, K.U., Kwon, D.S., 2007. The effect of sound on haptic perception. Proceedings of the 2nd Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC '07, 354–360).
Kitagawa, N., Zampini, M., Spence, C., 2005. Audiotactile interactions in near and far space. Exp. Brain Res. 166, 528–537.
Kitagawa, N., Spence, C., 2006. Audiotactile multisensory interactions in human information processing. Jpn. Psychol. Res. 48, 158–173.
Kitamura, E., Miyashita, K., Ozawa, K., Omata, M., Imamiya, A., 2006. Cross-modality between haptic and auditory roughness with a force feedback device. J. Rob. Mechatron. 18, 450–457.
Lederman, S.J., 1974. Tactile roughness of grooved surfaces: the touching process and effects of macro- and microsurface structure. Percept. Psychophys. 16, 385–395.
Lederman, S.J., 1979. Auditory texture perception. Perception 8, 93–103.
Lederman, S.J., Klatzky, R.L., Morgan, T., Hamilton, C., 2002. Integrating multimodal information about surface touch-produced sound sources. Proceedings of the 11th Annual Haptics Symposium for Virtual Environment and Teleoperator Systems (IEEE VR '03, 151–158).
McGee, M.R., Grai, P., Brewster, S., 2001. The effective combination of haptic and auditory textural information. Proceedings of the First international Workshop for Haptic Human–Computer Interaction (HCI 2000, 118–126).
Menning, H., Ackermann, H., Hertrich, I., Mathiak, K., 2005. Spatial auditory attention is modulated by tactile priming. Exp. Brain Res. 164, 41–47.
Meredith, M.A., Stein, B.E., 1986. Visual, auditory, and somatosensory convergence on cells in superior colliculus results in multisensory integration. J. Neurophysiol. 56, 640–662.
Moore, B.C.J., 1989. An Introduction to the Psychology of Hearing, 3rd ed. Academic Press, London.
Murray, M.M., Molholm, S., Michel, C.M., Heslenfeld, D.J., Ritter, W., Javitt, D.C., Schroeder, C.E., Foxe, J., 2005. Grabbing your ear: rapid auditory–somatosensory multisensory interactions in low-level sensory cortices are not constrained by stimulus alignment. Cereb. Cortex 15, 963–974.
Roland, P.E., O'sullivan, B., Kawashima, R., 1998. Shape and roughness activate different somatosensory areas in the human brain. Physiology 95, 3295–3300.
von Schiller, P., 1932. Die rauhigkeit als intermodale erscheinung. Zeit. Psychol. Bdg. 127, 265–289.
Spence, C., Zampini, M., 2006. Auditory contributions to multisensory product perception. Acta Acustica 92, 1009–1025.
Suzuki, Y., Suzuki, M., Gyoba, J., 2006. Effects of auditory feedback on tactile roughness perception. Tohoku Psychol. Folia 65, 45–56.
Terhardt, E., 1974. On the perception of periodic sound fluctuations (roughness). Acustica 30, 201–213.
Weisenberger, J.M., Poling, G.L., 2004. Multisensory roughness perception of virtual surfaces: effects of correlated cues. Proceedings of the 12th Annual Haptics Symposium for Virtual Environment and Teleoperator Systems (IEEE VR '04, 161–168).